

# The Galactic Center at High Energies

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I present here a review on the high energy phenomena occurring in the Galactic Center region, and report in particular on the results obtained from recent X-ray and gamma-ray observations.

## 1 The center of the Galaxy

The galactic center (GC) is a very dense and complex sky region of approximately 600 pc size ( $\sim 4^\circ$  in projection) where a number of interesting high-energy phenomena take place. Located at about 8 kpc distance it hosts the nearest super massive black hole (SMBH) surrounded by a variety of objects which interact with each other. The high energy processes generated in this extreme environment are possibly common to other galactic nuclei, and, given its proximity, the GC represents a unique laboratory for modern astronomy. Totally obscured in the optical wavelengths by the galactic plane, the GC is mainly observed from radio to infrared (IR) and again at high energies. Some important results have been recently obtained with the new generation of X-ray and gamma-ray observatories: Chandra, XMM-Newton, INTEGRAL and HESS. After a short introduction on the GC region (see also the reviews [32, 33, 20, 31]). I will summarize and discuss some of these results.

The beautiful radio image of the GC obtained with the VLA at 90 cm (Fig. 1 left) [25] shows all the complexity of this region. The GC contains  $\sim 10\%$  of the galactic interstellar medium (ISM), concentrated in the dense giant molecular clouds (MC) like Sgr B,

Sgr C and those of the Sgr A radio and molecular complex. Shell-like supernova remnants (SNR) heat the ISM with their expanding shells (e.g. G 359.1-005) which appear sometimes interacting with the MCs. While several other non-thermal filaments demonstrate the presence of accelerated particles spiralling the strong magnetic fields ( $\sim 1$  mG) of the region (like the large structure known as the *radio arc*, Fig. 1 right), other structures have thermal radio spectra and are in fact HII regions ionized by closeby hot and young star clusters. The central 30 pc are dominated by the Sgr A complex (Fig. 1 right), formed by few MCs (M-0.02-0.07, M-0.13-0.06) an expanding SNR, Sgr A East, and a central HII region surrounding the bright compact radio source Sgr A\*, the radio manifestation of the central SMBH. Sgr A East is a non-thermal radio source composed by a diffuse emission of triangular shape and an inner oval shell ( $7 \text{ pc} \times 9 \text{ pc}$  i.e.  $3' \times 4'$ ) centered about  $50''$  ( $\approx 2 \text{ pc}$ ) west of Sgr A\*. The shell appears in expansion, compressing the molecular cloud M-0.02-0.07 and probably creating the string of 4 HII regions and the OH masers observed around the shell. The first estimates of shell energy were well above the typical release of a SN, and it was proposed that Sgr A East was the result of 40 SN or of the explosive tidal disruption of a star by the SMBH. In the inner regions a rotating molecular ring surrounds Sgr A West, a thermal diffuse nebula with the characteristic shape of a minispiral, also rapidly rotating around the compact source Sgr A\*. Sgr A West is ionized by a cluster of hot young and massive stars, centered at about  $2''$  from Sgr A\* and known as IRS 16 (IRAS source). Some of these stars emit powerful stellar winds which interact with the surrounding medium and probably feed the SMBH.

While the matter dynamics at radial distances  $> 2 \text{ pc}$  is dominated by the central core of the galactic bulge star cluster, the large velocities of gas and stars observed in the innermost regions must imply the presence of a massive black hole. The adaptive optics NIR measures, made with the NTT, the VLT and the Keck over

the last 10-15 yr, of velocities and proper motions of the brightest and closest stars to Sgr A\* (the central star cluster) have by now provided precise orbital parameters for several of them [40, 14, 18]). The derived parameters imply the presence of a dark mass of  $3\text{--}4 \times 10^6 M_\odot$  enclosed within a radius  $< 100$  AU. Only a SMBH can explain such densities. The dynamical center of the central star cluster is coincident (within 10 mas) with the bright ( $\approx 1$  Jy), compact, variable, synchrotron (flat power law spectrum) radio source Sgr A\*. Since its discovery, 30 years ago, it has been considered the counterpart of the massive black hole of the Galaxy. The source is linearly polarized at sub-mm frequencies where the spectrum also present a bump indicating that the emission becomes optically thin. Sgr A\* proper motion is  $< 20$  km/s and its size, measured at frequencies of 3 mm where the interstellar scattering is small, is of the order of 0.1-0.3 mas, about  $15\text{--}20 R_S$ , where  $R_S = \frac{2GM}{c^2} = 10^{12}$  cm  $= 0.06$  AU is the Schwarzschild radius for a  $3.5 \times 10^6 M_\odot$  BH.

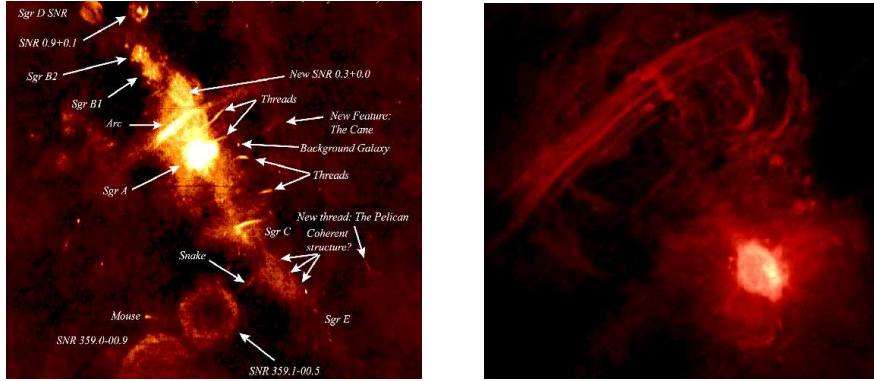


Figure 1: The Galactic center region seen with the VLA at 90 cm (La Rosa et al. 2000) (left) and the Sgr A complex with the radio arc seen with the VLA at 20 cm (Yusef-Zadeh et al. 2002, ApJ,570,665) (right).

## 2 The Galactic Center in the X-ray band

In the 2-10 keV X-ray band the GC has been deeply monitored by Chandra and XMM-Newton. It shows the following components: few bright sometimes transient X-ray binaries probably not associated to the GC (e.g. 1E1740.7-2942, 1E1743.1-2843); a large population of weak point-like persistent and transient sources; a diffuse emission with 3 distinct components, a soft thermal one ( $kT \sim 1$  keV, probably SNR heated gas), a hot component ( $kT \sim 8$  keV) and a nonthermal one characterized by a strong 6.4 keV line. Several SNR, non-thermal filaments and star clusters are also detected. The central 20 pc emission is dominated by the thermal emission from Sgr A East, while Sgr A\* itself appears very weak.

### 2.1 Quiescence and flaring activity of Sgr A\*

A SMBH surrounded by dense environment is an ideal system to generate accretion powered X-ray emission. And indeed the first reports of high energy emission from the GC direction were attributed to the SMBH. However as the resolution and sensitivity of the high energy telescopes increased it was realized that the galactic SMBH is a very weak, even in the hard X-ray domain (where BH binaries in hard state emit the bulk of their accretion luminosity) [19, 20]. The total (from radio to X-rays) Sgr A\* luminosity amounts to less than  $5 \cdot 10^{36}$  ergs  $s^{-1}$ , i.e. some  $10^{-8}$  times the Eddington luminosity of a  $3.5 \cdot 10^6 M_{\odot}$  BH. Since the IRS16 stellar winds are supposed to feed the BH at a rate of few  $10^{-4} M_{\odot} \text{ yr}^{-1}$  which implies accretion luminosities of  $0.02 L_E$ , this led to the development of theories of very inefficient accretion flows (e.g. the so called ADAF models) [31]. The Chandra observatory in 1999, with its unprecedented angular resolution of  $0.5''$  confirmed the very low X-ray luminosity of Sgr A\* ( $2 \cdot 10^{33}$  ergs  $s^{-1}$  in the 2-10 keV band) but measured a steep spectrum ( $\alpha \sim 2.5$ ), not compatible with the ADAF thermal

bremsstrahlung models ([5]). One year later Chandra made the dramatic discovery of a powerful X-ray flare from Sgr A\*. During this event, of a total duration of 3 hr, the flux increased by factor 50 to reach luminosities of  $10^{35}$  ergs s $^{-1}$  displaying a hard spectral slope ( $\alpha \sim 1.3$ ) [4]. XMM-Newton confirmed the presence of such bright hard flares from Sgr A\* [21] and discovered the most powerful one with an increase factor of 200 and, this time, a significantly steeper spectrum ( $\alpha \sim 2.5$ ) [38]. The flare duration (few hours) and the observed short time scales variations (200 s) indicate that the X-ray emission is produced within  $20 R_S$ . This cannot be accounted for by the standard ADAF model (for which the bulk of the X-ray emission is produced from the whole accretion flow starting at the accretion radius) and several other models are now considered where non-thermal emission plays a major role. The Liu and Melia model [26, 27] assumes that accreting matter circularizes in a small, very hot, magnetized keplerian disk where quasi relativistic electrons produce synchrotron radiation in the sub-mm band and, by inverse compton, the steep X-ray spectrum. Flares can be produced either by sudden increase in accretion rate or release of magnetic energy and the 2 different spectral slopes can be explained. Markoff et al. [28] locate the main energy release at the base of a relativistic jet rather than in the accretion disk. Substantial modification of ADAF models (inclusion of outflows, convection and non-thermal component) were also considered [43]. The different models can account for the observed spectral shapes but they predict different correlations between sub-mm, NIR and X-ray fluxes. The multiwavelength observation of Sgr A\* flares could allow to identify the correct model.

## 2.2 The diffuse X-ray emission

The Chandra and XMM-Newton surveys of the GC have also provided several new results on the diffuse emission. The first one

is the confirmation that the central few hundred parsecs are permeated by a hard diffuse emission peaked towards the center and extending along the plane, as observed by previous instruments and in particular by ASCA [24]. Continuum and line spectra of this emission [36, 34] (and in particular the strong 6.7 keV of ionized iron) seem to indicate that it is thermal with temperature of 8 keV. Such a hot plasma cannot be confined in the region by the gravitational potential, it would escape in  $< 4 \cdot 10^4$  yr and its origin is therefore unexplained (but see [9]). Chandra detected 2000 point-like weak sources in the central  $17' \times 17'$  but this population cannot explain more than 10% of the diffuse emission [34]. Some features of this component (the continuum is sometimes associated to the 6.4 keV line rather than the 6.7 keV one) are difficult to reconcile with a thermal nature and few authors have proposed non-thermal origin, i.e. cosmic ray interaction with ISM [42, 44], or effect of SN ejecta in dense regions [10]. Indeed the other distinct component of the GC diffuse emission is the 6.4 keV line of neutral or weakly ionized iron, which has a different morphology than the 6.7 keV line and is certainly due to non-thermal processes, involving reprocessing of external high energy radiation or cosmic ray interactions with dense MC.

### 2.3 Sgr B2 and Sgr A East

The 6.4 keV image of the region shows a very strong peak at the position of the Sgr B2 GMC. This was interpreted as fluorescent line due to scattering of hard X-ray emission coming from an external source, possibly Sgr A\* itself [24, 35]. A strong transient outburst of hard X-rays from the SMBH occurred some 300 yr back would have travelled the distance to Sgr B2 illuminating the dense cloud and generating the Fe line along with hard X-ray emission. Such hard ( $> 10$  keV) scattered emission was initially detected with GRANAT/ART-P and now with INTEGRAL [41]. The X-ray ob-

servations of the Sgr A complex have also demonstrated that the bright X-ray source Sgr A East is a mixed morphology SNR, where the non-thermal radio shell surrounds a centrally peaked thermal X-ray emission [29]. The X-ray plasma has 2 components, one at 1 keV and the other at 4 keV [39]. High abundances in the center of source indicate that part of emission is due to the heated SN ejecta. Most recent Chandra results on Sgr A East have shown evidences that one of the sources of the region could be the kicked off NS from a SN II explosion [37]. However the X-ray data show now that Sgr A East, apart from the high plasma temperature and from beeing in expantion against a very dense medium, is not an exceptional SNR. It appears to be the product of a typical SN II or a SN Ia occured about  $10^4$  yr. Assuming a certain distance of the SN from Sgr A\*, the shell of swept up ISM could have reached the SMBH feeding it and triggerig a Sgr A\* outburst of hard emission, later reflected by Sgr B2 [29].

## 2.4 The recent results

The years 2003 and 2004 have seen several new developments in the domain. In particular a series of large multiwavelength campaigns have been performed in order to obtain broad band measures on the variable emission from Sgr A\*. In 2003, the VLT [16], followed by the Keck [18], could reveal that Sgr A\* is flaring also in the NIR band. The NIR flares appear more frequent (several / day) than the X-ray ones ( $\sim 1$  /day) and their red spectra extending in the MIR domain [14, 17, 11] confirm that synchrotron is the dominant IR radiation mechanism. The IR observations also provided the spectacular evidence that the emission appears modulated with a period of 17 mn [16]. If such a period is associated to the last stable orbit of an accretion disk such timescale implies that the SMBH is rotating at 50% of the maximum allowed spin. Revisiting X-ray flare variability Aschebach et al. [3] found a serie of possible

quasi periods in the power spectra. These periods appear in relation to the characteristic frequencies (keplerian, vertical and radial oscillations) of a disk orbiting around a BH with maximum spin. Although these results are extremely exciting they are still rather controversial and the reported X-ray periodicities from Sgr A\* need to be confirmed by more significant measurements. Firm detections of QPO from Sgr A\* with periods in the range 15-30 mn would certainly favor the accretion disk models and would provide strong constraints on the mass and spin of the SMBH at the GC. The first flare simultaneously observed in IR and X-rays was detected using Chandra and the VLT [13]. The flare was however very weak and a much stronger event was observed simultaneously with XMM and the HST during the large 2004 multiwavelength observation campaign of Sgr A\* [45]. This campaign based on a XMM-Newton large project involved radio (VLA, ATCA), sub-mm (CSO, SMT, NMA, BIMA), IR (VLT, HST) and gamma-ray (INTEGRAL, HESS) observatories. Two bright (factor 35) X-ray flares were observed with XMM-Newton (Fig. 3) [7] and the September one could be observed with the NICMOS camera of the HST. The NIR and X-ray flares are very similar in shape and the lack of time lags and the measured spectral slopes may indicate that X-rays are indeed produced by inverse compton scattering of the same electrons that produce the NIR synchrotron emission off the sub-mm-radiation [45].

### 3 The Galactic Center in gamma-rays

The INTEGRAL observatory monitored, with the IBIS/ISGRI telescope, the GC region for more than 7 Ms between 2003 and 2004, obtaining, with an effective exposure of 4.7 Ms, the most precise images of the GC ever collected in the 20-600 keV band [6, 22, 8]. In addition to the bright X-ray binaries INTEGRAL detected a faint and persistent high energy emission coming from the very center of the Galaxy (Fig. 2), compatible (within the 1' error radius)



with Sgr A\*. Due to the IBIS angular resolution ( $\sim 13'$  FWHM) this source (IGR J17456–2901) cannot be clearly associated to the SMBH or to other objects of the dense central region. The lack of variability and of a bright discrete X-ray counterpart suggest that it is rather a compact and yet diffuse emission. The INTEGRAL spectrum was compared to the 1-10 keV one obtained from XMM-Newton (partly simultaneous) data integrating over the region of the IBIS point spread function [8]. The spectra combine well (Fig. 2), but the thermal plasma with kT of 8 keV used to model the bulk of the X-ray diffuse emission cannot explain the data at  $> 20$  keV, neither can the contributions of the transient point sources seen by Chandra or XMM. A non-thermal component extending up to 120-200 keV with spectral slope of photon index 3 is clearly present and its origin is still unexplained. Simultaneous XMM-INTEGRAL observations performed during the 2004 campaign are not conclusive on the possible detection with INTEGRAL of the Sgr A\* X-ray flares since the 2 events observed with XMM occurred during the INTEGRAL passage into the radiation belts (Fig. 3). However, even if the Sgr A\* X-ray flares extend at  $> 20$  keV with their hard slope, they are too sparse to fully account for the gamma-ray source. In addition, INTEGRAL observed constant hard emission, from Sgr B2 (IGR J17475-2822 in Fig. 2). This strongly confirm the thesis of a reflection nebula for Sgr B2 [41].

IGR J17456–2901 could be linked to the VHE gamma-ray emission observed by several Atmospheric Cherenkov Detectors. HESS, the most sensitive and precise of them, reported the presence of a TeV source centered within  $1'$  from Sgr A\* [1] (Fig. 4). The source is constant and display power-law spectrum extending from 300 GeV up to 10 TeV. This emission cannot be explained by heavy dark matter particle annihilation and is probably due to interactions of particles accelerated at very high energies. However the mechanism and site of acceleration, the expanding shell of the Sgr A East SNR

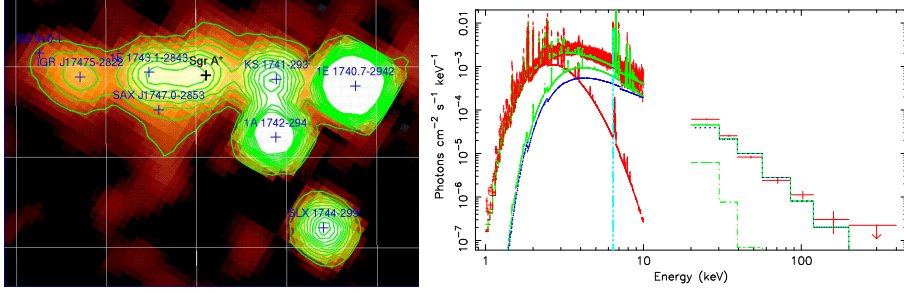


Figure 2: The 20-40 keV INTEGRAL/IBIS images of the GC showing the source in Sgr A (left) and combined XMM-IBIS spectrum for this excess (right)

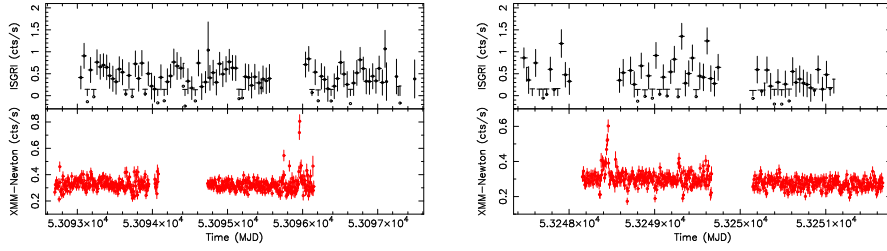


Figure 3: The 20-30 keV INTEGRAL/IBIS light curves (black) of the central source in March (left) and Sep. (right) 2004. The 2 Sgr A\* flares in the XMM 2-10 keV light curves (red) occur during INTEGRAL radiation belt passages.

[12] or the regions close to the SMBH horizon [2], are not yet identified. The EGRET source observed between 50 MeV and 10 GeV (3EG J1746-2852) located at  $0.2^\circ$  from Sgr A\* [30, 23] seems too far to be the 1 GeV counterpart for the INTEGRAL and the HESS sources, but in this complex region the EGRET data are not conclusive. Gamma-ray emission from the GC has now been clearly detected but its origin and nature are not yet understood.

The Chandra, XMM-Newton, INTEGRAL and HESS monitoring of the GC will continue in the coming months/years, hopefully coupled to NIR, sub-mm and radio correlated observing programs. These programs will possibly settle the issue of periodicities in the X-ray flares and will provide measures of the broad band spectra of

the Sgr A\* flares. Solving the puzzle of the hard X-ray emission will however necessitate focusing instruments in this energy domain, as Simbol-X expected to fly at the beginning of the next decade [15]. In the near future GLAST will probably unveil the mystery of the EGRET source at the GC and the next generation of ACD detectors will map the region at TeV energies with increased precision.

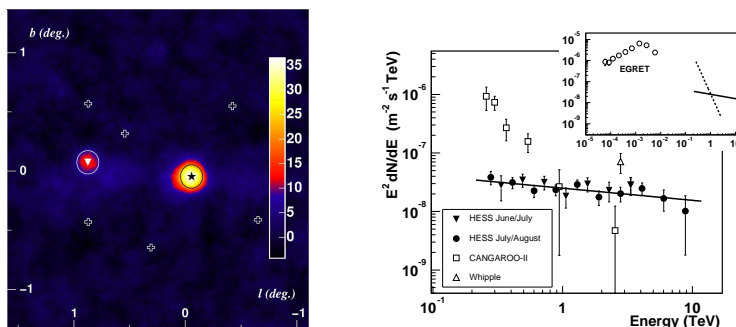


Figure 4: HESS image of the GC showing the source in Sgr A (star) (Aharonian et al. 2005 *A&A* 432 L25) (left) and the HESS spectrum of this source (right).

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